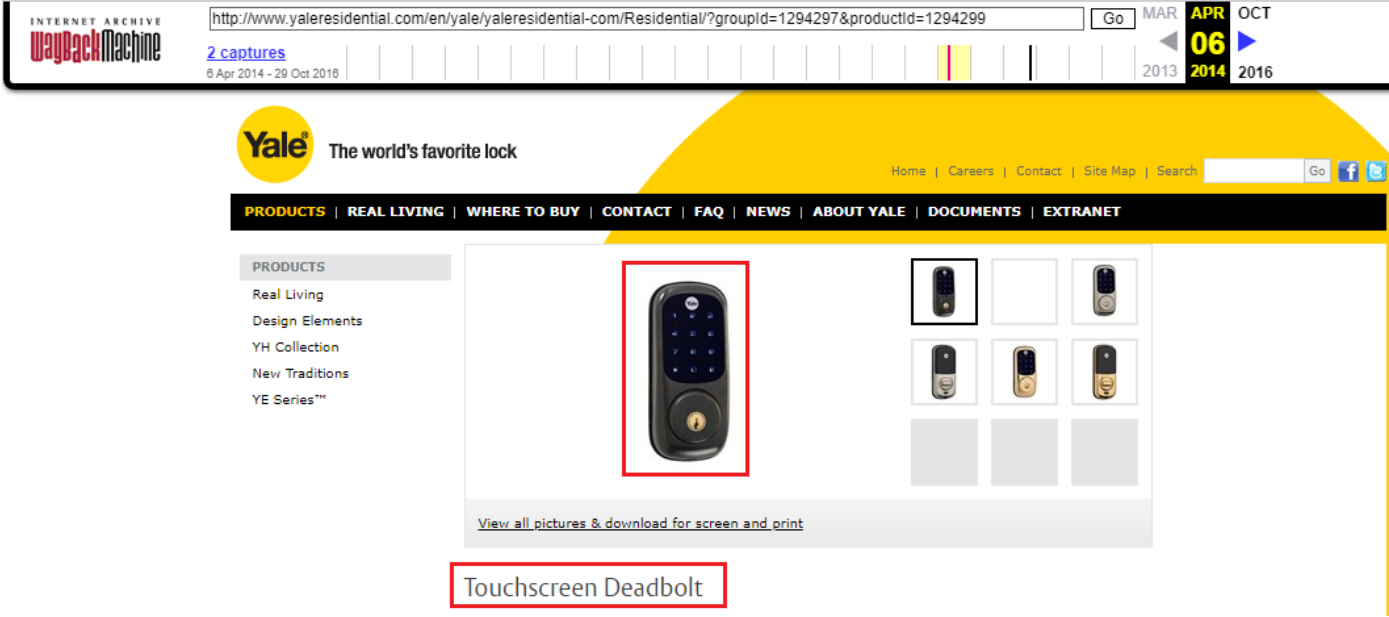


# **EXHIBIT B**

US6671307	Yale's YRD220 (ZigBee Version) Touchscreen Deadbolt ("Accused Product")
3. An improvement to a spread-spectrum transmitter for sending data over a communications channel, comprising:	<p>The accused product comprises a spread-spectrum transmitter (e.g., ZigBee transceiver/SOC) for sending data over a communications channel (e.g., Wireless channel).</p>  <p>The screenshot shows the Yale Residential website. The URL in the address bar is <a href="http://www.yaleresidential.com/en/yale/yaleresidential-com/Residential/?groupId=1294297&amp;productId=1294299">http://www.yaleresidential.com/en/yale/yaleresidential-com/Residential/?groupId=1294297&amp;productId=1294299</a>. The page features the Yale logo and navigation links. A sidebar lists product categories: PRODUCTS, Real Living, Design Elements, YH Collection, New Traditions, and YE Series™. The main content area displays a large image of the YRD220 Touchscreen Deadbolt, which is highlighted with a red box. Below this image is a link that says "View all pictures &amp; download for screen and print". To the right of the main image are several smaller thumbnail images of other Yale lock models. At the bottom of the page, the text "Touchscreen Deadbolt" is highlighted with a red box.</p> <p><a href="https://web.archive.org/web/20140406224400/http://www.yaleresidential.com/en/yale/yaleresidential-com/Residential/?groupId=1294297&amp;productId=1294299">https://web.archive.org/web/20140406224400/http://www.yaleresidential.com/en/yale/yaleresidential-com/Residential/?groupId=1294297&amp;productId=1294299</a></p>

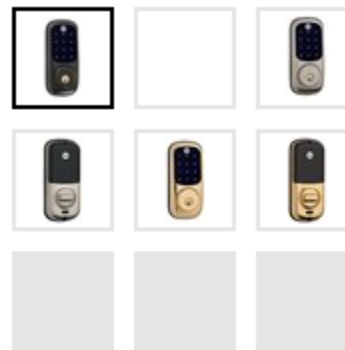
## Deadbolt Selection



YRD210 Push Button Deadbolt   **YRD220 Touchscreen Deadbolt**   YRD240 Key Free Touchscreen Deadbolt  
US3 Polished Brass • US15 Satin Nickel • US10BP Oil Rubbed Bronze Permanent

[https://www.yalehome.com/Yale/Yale%20US/Brochures/Yale\\_Real\\_Living\\_Brochure\\_8.5x11\\_099800.pdf](https://www.yalehome.com/Yale/Yale%20US/Brochures/Yale_Real_Living_Brochure_8.5x11_099800.pdf)

Alternate Source: [Touchscreen Deadbolt YRD220](#)



[View all pictures & download for screen and print](#)

## Touchscreen Deadbolt

### Description

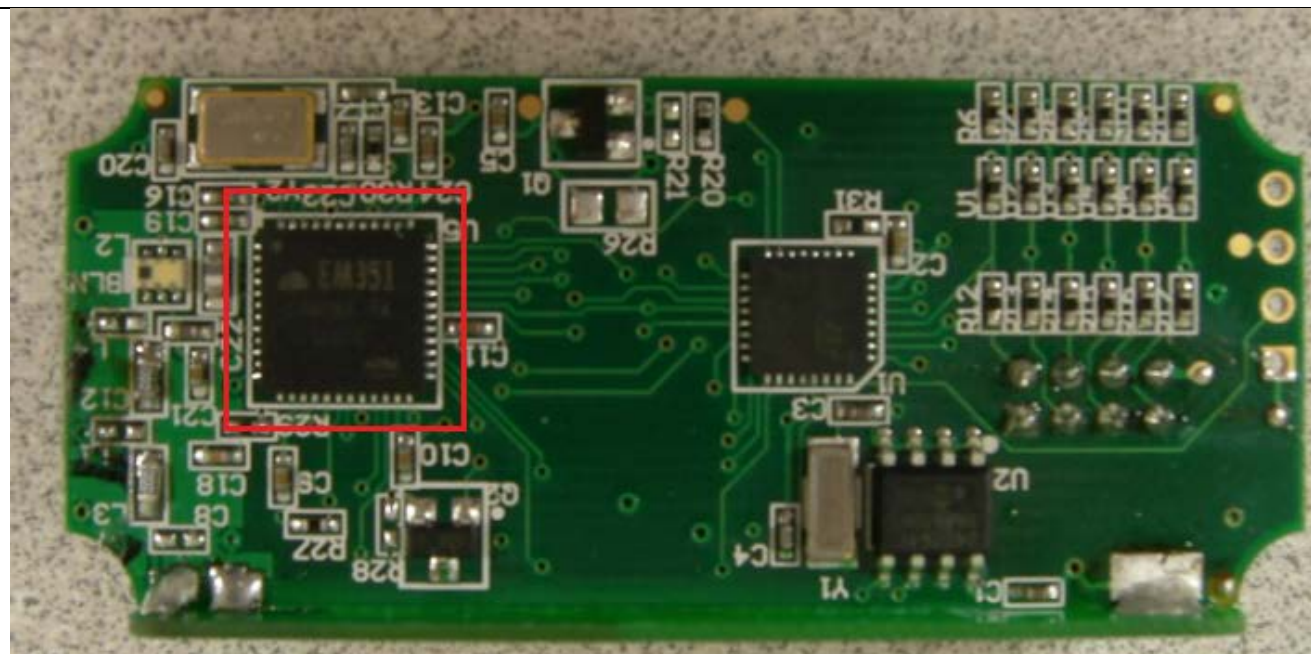


#### Design Features

- Available in both durable acrylic touchscreen or simple, elegant, tamper-resistant keypad
- Illuminated touchscreen and keypad for night time access
- For use on all standard interior and exterior doors
- Tapered bolt accommodates misaligned doors
- Available in ZigBee or Z-Wave configurations

<https://web.archive.org/web/20140406224400/http://www.yaleresidential.com/en/yale/yaleresidential-com/Residential/?groupId=1294297&productId=1294299>

As shown below, the accused product contains a 2.4 GHz ZigBee Transceiver (EMBER's 351 ZigBee Radio).



As depicted below, ZigBee standard is built on top of IEEE 802.15.4. Also presented below is the specifications of EMBER's 351 ZigBee SOC.



## EM351/EM357

High-Performance, Integrated ZigBee/802.15.4 System-on-Chip

### Features

- 32-bit ARM® Cortex -M3 processor
- 2.4 GHz IEEE 802.15.4-2003 transceiver & lower MAC
- 128 or 192 kB flash, with optional read protection
- 12 kB RAM memory
- AES128 encryption accelerator
- Flexible ADC, UART/SPI/TWI serial communications, and general purpose timers
- 24 highly configurable GPIOs with Schmitt trigger inputs

### Industry-leading ARM® Cortex -M3 processor

- Leading 32-bit processing performance
- Highly efficient Thumb-2 instruction set
- Operation at 6, 12, or 24 MHz
- Flexible Nested Vectored Interrupt Controller

### Low power consumption, advanced management

- RX Current (w/ CPU): 26 mA
- TX Current (w/ CPU, +3 dBm TX): 31 mA
- Low deep sleep current, with retained RAM and GPIO: 400 nA without/800 nA with sleep timer
- Low-frequency internal RC oscillator for low-power sleep timing
- High-frequency internal RC oscillator for fast (110 µs) processor start-up from sleep

### Exceptional RF Performance

- Normal mode link budget up to 103 dB; configurable up to 110 dB
- -100 dBm normal RX sensitivity; configurable to -102 dBm (1% PER, 20 byte packet)
- +3 dB normal mode output power; configurable up to +8 dBm
- Robust Wi-Fi and Bluetooth coexistence

### Innovative network and processor debug

- Packet Trace Port for non-intrusive packet trace with Ember development tools
- Serial Wire/JTAG interface
- Standard ARM debug capabilities: Flash Patch & Breakpoint; Data Watchpoint & Trace; Instrumentation Trace Macrocell

### Application Flexibility

- Single voltage operation: 2.1–3.6 V with internal 1.8 and 1.25 V regulators
- Optional 32.768 kHz crystal for higher timer accuracy
- Low external component count with single 24 MHz crystal
- Support for external power amplifier
- Small 7x7 mm 48-pin QFN package

<https://www.silabs.com/documents/public/data-sheets/EM35x.pdf>

## What is ZigBee Technology

*Zigbee has been established for many years as an IoT network standard for remote control and sensing applications.*

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### **Zigbee Includes:**

[Zigbee technology basics](#)

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The Zigbee standard is a standard built on top of IEEE 802.15.4 which provides the upper layers for control and sensor applications.

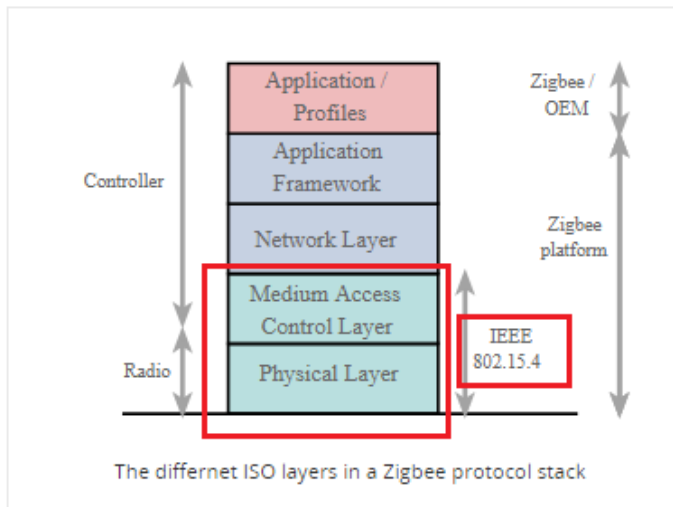
It has been designed to be very robust so that it can operate reliably in harsh radio environments, providing security and flexibility.

As an open standard, Zigbee is able to operate using items from a variety of manufacturers.

<https://www.electronics-notes.com/articles/connectivity/zigbee/what-is-zigbee-technology-tutorial.php>

## ZigBee basics

The distances that can be achieved transmitting from one station to the next extend up to about 70 metres, although very much greater distances may be reached by relaying data from one node to the next in a network.



<https://www.electronics-notes.com/articles/connectivity/zigbee/what-is-zigbee-technology-tutorial.php>

Zigbee products use very low power and are available at very low cost. They are based on LR-WPAN (low rate wireless personal area network) standard i.e. IEEE 802.15.4. Zigbee products will have protocol layers (PHY, MAC, network, security, application). Network, security and application layers are defined by zigbee alliance.

<http://www.rfwireless-world.com/Terminology/what-is-zigbee.html>

As shown below, ZigBee is a DSSS based technology. DSSS, also referred to as “Direct Sequence Spread Spectrum”, is a type of spread spectrum technology.

### **Physical and MAC layers**

The system is specified to operate in one of the three license free bands at 2.4 GHz, 915 MHz for North America and 868 MHz for Europe. In this way the standard is able to operate around the globe, although the exact specifications for each of the bands are slightly different. At 2.4 GHz there are a total of sixteen different channels available, and the maximum data rate is 250 kbps. For 915 MHz there are ten channels and the standard supports a maximum data rate of 40 kbps, while at 868 MHz there is only one channel and this can support data transfer at up to 20 kbps.

The modulation techniques also vary according to the band in use. Direct sequence spread spectrum (DSSS) is used in all cases. However for the 868 and 915 MHz bands the actual form of modulation is binary phase shift keying. For the 2.4 GHz band, offset quadrature phase shift keying (O-QPSK) is employed.

In view of the fact that systems may operate in heavily congested environments, and in areas where levels of extraneous interference is high, the 802.15.4 specification has incorporated a variety of features to ensure exceedingly reliable operation. These include a quality assessment, receiver energy detection and clear channel assessment. CSMA (Carrier Sense Multiple Access) techniques are used to determine when to transmit, and in this way unnecessary clashes are avoided.

<https://www.electronics-notes.com/articles/connectivity/zigbee/what-is-zigbee-technology-tutorial.php>

The accused product operates in 2.4 GHz range.

## Zigbee Physical Layer(PHY)

There are two **Physical layer** formats one each for 868/915MHz and 2450MHz bands in **Zigbee** standard. 868-868.6 MHz zigbee band delivers about 20Ksymbol/s with BPSK modulation employed. 902-928 MHz band delivers about 40 Ksymbol/s with BPSK modulation. 2400-2483.5 MHz delivers about 62.5 Ksymbol/s with O-QPSK modulation.

<http://www.rfwireless-world.com/Tutorials/Zigbee-physical-layer.html>



Shown below are excerpts from 802.15.4 which defines physical layer of ZigBee standard. The modulation scheme employed by the accused product is O-QPSK since it operates in 2.4 GHz range. There are total 16 Channels (numbered from 11 to 26) in 2.4GHz operation.

## 6. PHY specification

This clause specifies two PHY options for IEEE 802.15.4. The PHY is responsible for the following tasks:

- Activation and deactivation of the radio transceiver
- ED within the current channel
- LQI for received packets
- CCA for CSMA-CA
- Channel frequency selection
- Data transmission and reception

Constants and attributes that are specified and maintained by the PHY are written in the text of this clause in italics. Constants have a general prefix of “a”, e.g., *aMaxPHYPacketSize*, and are listed in Table 18. Attributes have a general prefix of “phy”, e.g., *phyCurrentChannel*, and are listed in Table 19.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

### IEEE Std 802.15.4-2003

This standard defines the protocol and interconnection of devices via radio communication in a personal area network (PAN). The standard uses carrier sense multiple access with a collision avoidance medium access mechanism and supports star as well as peer-to-peer topologies. The media access is contention based; however, using the optional superframe structure, time slots can be allocated by the PAN coordinator to devices with time critical data. Connectivity to higher performance networks is provided through a PAN coordinator.

This standard specifies two PHYs: an 868/915 MHz direct sequence spread spectrum (DSSS) PHY and a 2450 MHz DSSS PHY. The 2450 MHz PHY supports an over-the-air data rate of 250 kb/s, and the 868/915 MHz PHY supports over-the-air data rates of 20 kb/s and 40 kb/s. The PHY chosen depends on local regulations and user preference.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.1.1 Operating frequency range**

A compliant device shall operate in one or several frequency bands using the modulation and spreading formats summarized in Table 1.

**Table 1—Frequency bands and data rates**

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.1.2 Channel assignments and numbering**

A total of 27 channels, numbered 0 to 26, are available across the three frequency bands. Sixteen channels are available in the 2450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 868.3 \text{ in megahertz, for } k = 0$$

$$F_c = 906 + 2(k - 1) \text{ in megahertz, for } k = 1, 2, \dots, 10$$

$$\text{and } F_c = 2405 + 5(k - 11) \text{ in megahertz, for } k = 11, 12, \dots, 26$$

where

$k$  is the channel number.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

## 6.5 2450 MHz PHY specifications

The requirements for the 2450 MHz PHY are specified in 6.5.1 through 6.5.3.

### 6.5.1 Data rate

The data rate of the IEEE 802.15.4 (2450 MHz) PHY shall be 250 kb/s.

### 6.5.2 Modulation and spreading

The 2450 MHz PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK).

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

## Physical and MAC layers

The system is specified to operate in one of the three license free bands at 2.4 GHz, 915 MHz for North America and 868 MHz for Europe. In this way the standard is able to operate around the globe, although the exact specifications for each of the bands are slightly different. At 2.4 GHz there are a total of sixteen different channels available, and the maximum data rate is 250 kbps. For 915 MHz there are ten channels and the standard supports a maximum data rate of 40 kbps, while at 868 MHz there is only one channel and this can support data transfer at up to 20 kbps.

The modulation techniques also vary according to the band in use. Direct sequence spread spectrum (DSSS) is used in all cases. However for the 868 and 915 MHz bands the actual form of modulation is binary phase shift keying. For the 2.4 GHz band, offset quadrature phase shift keying (O-QPSK) is employed.

In view of the fact that systems may operate in heavily congested environments, and in areas where levels of extraneous interference is high, the 802.15.4 specification has incorporated a variety of features to ensure exceedingly reliable operation. These include a quality assessment, receiver energy detection and clear channel assessment. CSMA (Carrier Sense Multiple Access) techniques are used to determine when to transmit, and in this way unnecessary clashes are avoided.

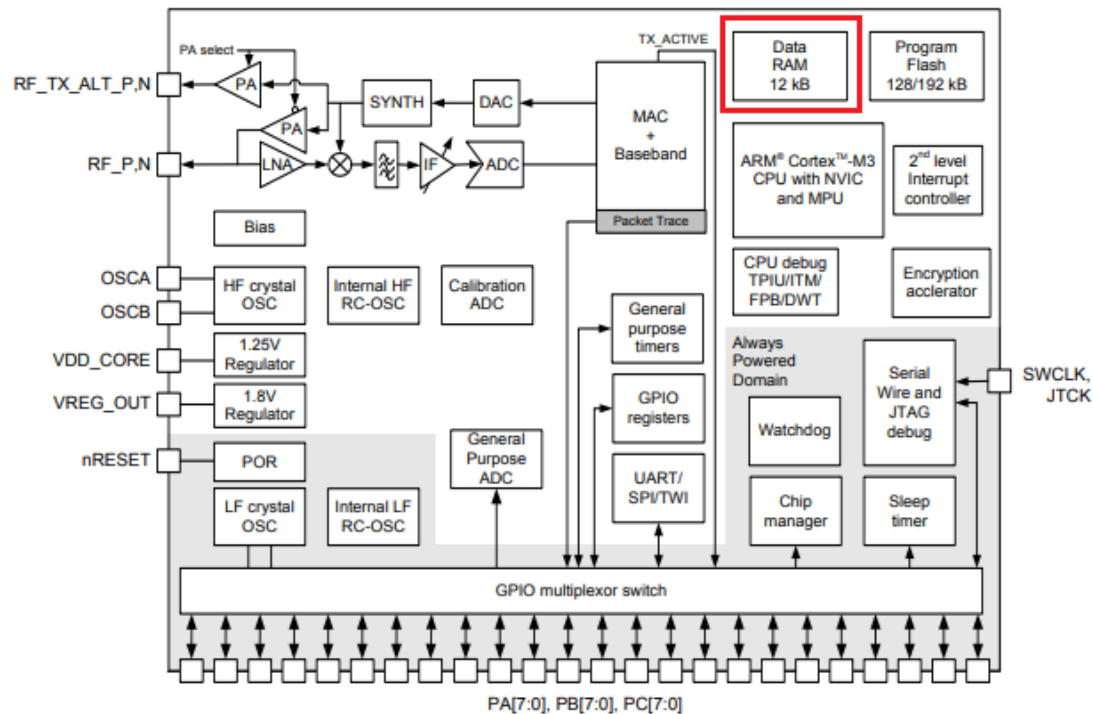
<https://www.electronics-notes.com/articles/connectivity/zigbee/what-is-zigbee-technology-tutorial.php>

a memory for storing N bits of data as stored data, with N a number of bits in a symbol;

The spread-spectrum transmitter (e.g., ZigBee transceiver) utilized by the accused product comprises a memory (e.g., data RAM) for storing N (e.g., N=4) bits of data as stored data, with N (e.g., N=4) representing a number of bits in a symbol.

As shown below, the spread-spectrum transmitter (e.g., ZigBee transceiver) utilized by the accused product maps 4 bits into one data symbol and thereafter stores it in a memory/buffer.

Figure 3.1 shows a detailed block diagram of the EM35x.



**Figure 3.1. EM35x Block Diagram**

<https://www.silabs.com/documents/public/data-sheets/EM35x.pdf>



## EM351/EM357

High-Performance, Integrated ZigBee/802.15.4 System-on-Chip

### Features

- 32-bit ARM® Cortex -M3 processor
- 2.4 GHz IEEE 802.15.4-2003 transceiver & lower MAC
- 128 or 192 kB flash, with optional read protection
- 12 kB RAM memory
- AES128 encryption accelerator
- Flexible ADC, UART/SPI/TWI serial communications, and general purpose timers
- 24 highly configurable GPIOs with Schmitt trigger inputs

### Industry-leading ARM® Cortex -M3 processor

- Leading 32-bit processing performance
- Highly efficient Thumb-2 instruction set
- Operation at 6, 12, or 24 MHz
- Flexible Nested Vectored Interrupt Controller

### Low power consumption, advanced management

- RX Current (w/ CPU): 26 mA
- TX Current (w/ CPU, +3 dBm TX): 31 mA
- Low deep sleep current, with retained RAM and GPIO: 400 nA without/800 nA with sleep timer
- Low-frequency internal RC oscillator for low-power sleep timing
- High-frequency internal RC oscillator for fast (110 µs) processor start-up from sleep

### Exceptional RF Performance

- Normal mode link budget up to 103 dB; configurable up to 110 dB
- -100 dBm normal RX sensitivity; configurable to -102 dBm (1% PER, 20 byte packet)
- +3 dB normal mode output power; configurable up to +8 dBm
- Robust Wi-Fi and Bluetooth coexistence

### Innovative network and processor debug

- Packet Trace Port for non-intrusive packet trace with Ember development tools
- Serial Wire/JTAG interface
- Standard ARM debug capabilities: Flash Patch & Breakpoint; Data Watchpoint & Trace; Instrumentation Trace Macrocell

### Application Flexibility

- Single voltage operation: 2.1–3.6 V with internal 1.8 and 1.25 V regulators
- Optional 32.768 kHz crystal for higher timer accuracy
- Low external component count with single 24 MHz crystal
- Support for external power amplifier
- Small 7x7 mm 48-pin QFN package

<https://www.silabs.com/documents/public/data-sheets/EM35x.pdf>

**6.5.2.1 Reference modulator diagram**

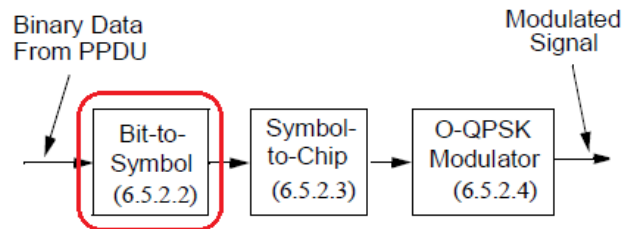
The functional block diagram in Figure 18 is provided as a reference for specifying the 2450 MHz PHY modulation and spreading functions. The number in each block refers to the subclause that describes that function.

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IEEE  
Std 802.15.4-2003

IEEE STANDARD FOR LOCAL AND METROPOLITAN AREA NETWORKS:



**Figure 18—Modulation and spreading functions**

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.5.2.2 Bit-to-symbol mapping**

All binary data contained in the PPDU shall be encoded using the modulation and spreading functions shown in Figure 18. This subclause describes how binary information is mapped into data symbols.

The 4 LSBs ( $b_0, b_1, b_2, b_3$ ) of each octet shall map into one data symbol, and the 4 MSBs ( $b_4, b_5, b_6, b_7$ ) of each octet shall map into the next data symbol. Each octet of the PPDU is processed through the modulation and spreading functions (see Figure 18) sequentially, beginning with the preamble field and ending with the last octet of the PSDU. Within each octet, the least significant symbol ( $b_0, b_1, b_2, b_3$ ) is processed first and the most significant symbol ( $b_4, b_5, b_6, b_7$ ) is processed second.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

a chip-sequence

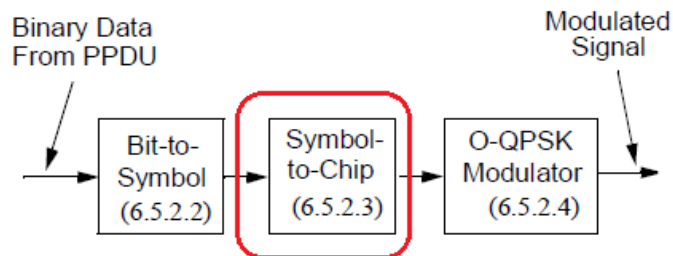
The spread-spectrum transmitter (e.g., ZigBee transceiver) utilized by the accused product comprises a chip-

encoder, coupled to said memory, for selecting, responsive to the N bits of stored data, a chip-sequence signal from a plurality of chip-sequence signals stored in said chip-sequence encoder, as an output chip-sequence signal; and

sequence encoder (e.g., symbol to chip mapper), coupled to said memory, for selecting, responsive to the N (e.g., N=4) bits of stored data, a chip-sequence signal (e.g., PN Sequence) from a plurality of chip-sequence signals (e.g., 16 PN Sequences) stored in said chip-sequence encoder (e.g., symbol to chip mapper), as an output chip-sequence signal (e.g., PN Sequence).

IEEE  
Std 802.15.4-2003

IEEE STANDARD FOR LOCAL AND METROPOLITAN AREA NETWORKS:



**Figure 18—Modulation and spreading functions**

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

### **6.5.2 Modulation and spreading**

The 2450 MHz PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK).

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.5.2.3 Symbol-to-chip mapping**

Each data symbol shall be mapped into a 32-chip PN sequence as specified in Table 20. The PN sequences are related to each other through cyclic shifts and/or conjugation (i.e., inversion of odd-indexed chip values).

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

As shown below, for each symbol, which comprises 4-bits, 1 of 16 PN sequences are selected. Symbol to chip mapper comprises a table which has sixteen 32-bit PN Sequences (chip values) corresponding to each of sixteen 4-bit data symbol.

**6.5.2.3 Symbol-to-chip mapping**

Each data symbol shall be mapped into a 32-chip PN sequence as specified in Table 20. The PN sequences are related to each other through cyclic shifts and/or conjugation (i.e., inversion of odd-indexed chip values).

**Table 20—Symbol-to-chip mapping**

Data symbol (decimal)	Data symbol (binary) ( $b_0, b_1, b_2, b_3$ )	Chip values ( $c_0, c_1, \dots, c_{30}, c_{31}$ )
0	0000	11011001110000110101001000101110
1	1000	11101101100111000011010100100010
2	0100	00101110110110011100001101010010
3	1100	00100010111011011001110000110101
4	0010	01010010001011101101100111000011
5	1010	00110101001000101110110110011100
6	0110	11000011010100100010111011011001
7	1110	10011100001101010010001011101101
8	0001	10001100100101100000011101111011
9	1001	10111000110010010110000001110111
10	0101	01111011100011001001011000000111
11	1101	01110111101110001100100101100000
12	0011	00000111011110111000110010010110
13	1011	01100000011101111011100011001001

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

WIRELESS MAC AND PHY SPECIFICATIONS FOR LR-WANS IEEE  
Std 802.15.4-2003

**Table 20—Symbol-to-chip mapping (continued)**

Data symbol (decimal)	Data symbol (binary) ( $b_0, b_1, b_2, b_3$ )	Chip values ( $c_0, c_1, \dots, c_{30}, c_{31}$ )
14	0 1 1 1	1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 1 1	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

a transmitter section, coupled to said chip-sequence encoder, for transmitting the output chip-sequence signal as a radio wave, at a carrier frequency, over said communications channel, as a spread-spectrum signal.

The spread-spectrum transmitter (e.g., ZigBee transceiver) utilized by the accused product comprises a transmitter section (e.g., a transmitter path section which uses front end and digital baseband), coupled to said chip-sequence encoder (e.g., symbol to chip mapper), for transmitting the output chip-sequence signal (e.g., the selected PN sequence for a data symbol) as a radio wave (e.g., modulated RF signal), at a carrier frequency (at a carrier frequency of one of 16 carrier frequencies identified by 2.405 MHz, 2.410 MHz, 2.415 MHz, 2.420 MHz, 2.425 MHz, 2.430 MHz, 2.435 MHz, 2.440 MHz, 2.445 MHz, 2.450 MHz, 2.455 MHz, 2.460 MHz, 2.465 MHz, 2.470 MHz, 2.475 MHz, and 2.480 MHz), over said communications channel (e.g., wireless channel), as a spread-spectrum signal.

## **4.2. Transmit (TX) Path**

The EM35x TX path produces an O-QPSK-modulated signal using the analog front end and digital baseband. The area- and power-efficient TX architecture uses a two-point modulation scheme to modulate the RF signal generated by the synthesizer. The modulated RF signal is fed to the integrated PA and then out of the EM35x.

### **4.2.1. TX Baseband**

The EM35x TX baseband in the digital domain spreads the 4-bit symbol into its IEEE 802.15.4-2003-defined 32-chip sequence. It also provides the interface for the Ember software to calibrate the TX module to reduce silicon process, temperature, and voltage variations.

### **4.2.2. TX\_ACTIVE and nTX\_ACTIVE Signals**

For applications requiring an external PA, two signals are provided called TX\_ACTIVE and nTX\_ACTIVE. These signals are the inverse of each other. They can be used for external PA power management and RF switching logic. In transmit mode the TX baseband drives TX\_ACTIVE high, as described in Table 7.5 on page 57. In receive mode the TX\_ACTIVE signal is low. TX\_ACTIVE is the alternate function of PC5, and nTX\_ACTIVE is the alternate function of PC6. See "7. GPIO (General Purpose Input/Output)" on page 50 for details of the alternate GPIO functions. The digital I/O that provide these signals have a 4 mA output sink and source capability.

<https://www.silabs.com/documents/public/data-sheets/EM35x.pdf>

Figure 3.1 shows a detailed block diagram of the EM35x.

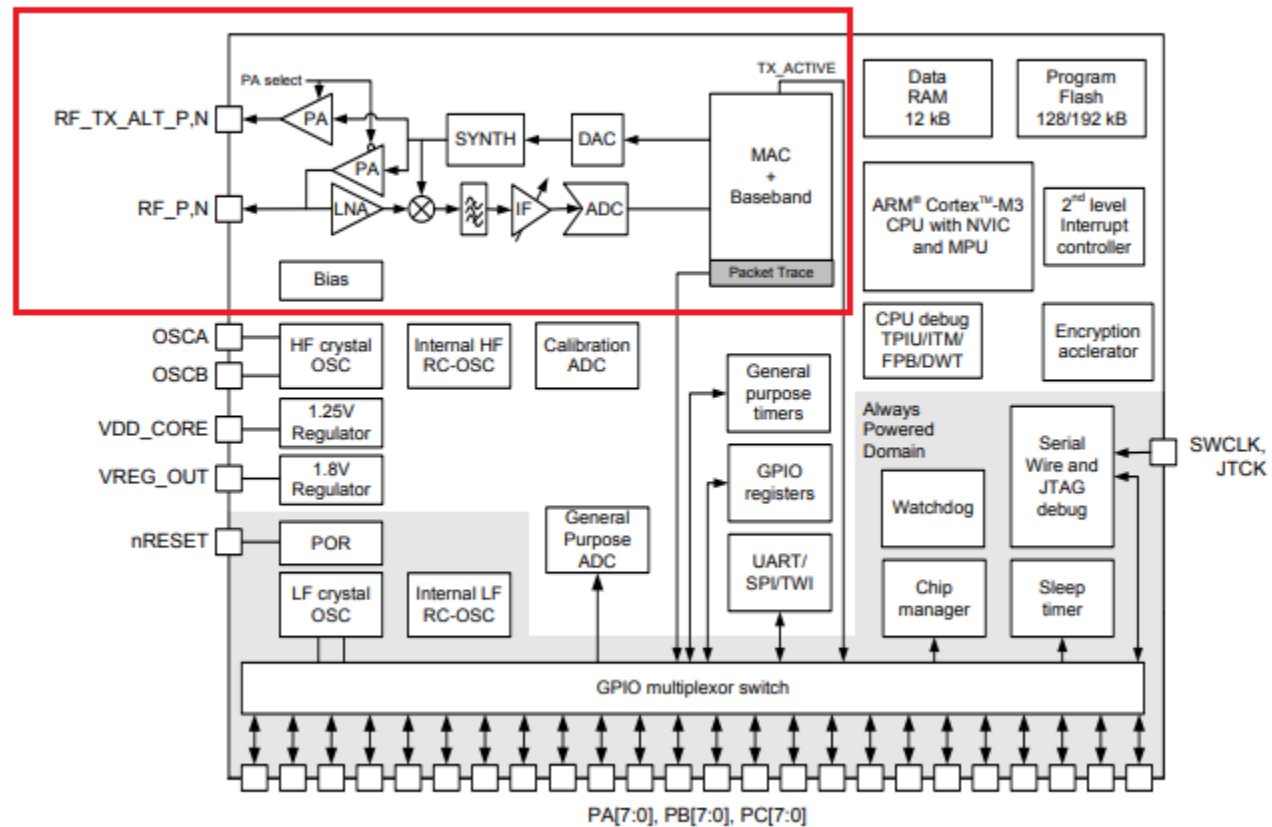


Figure 3.1. EM35x Block Diagram

<https://www.silabs.com/documents/public/data-sheets/EM35x.pdf>

## Physical and MAC layers

The system is specified to operate in one of the three license free bands at 2.4 GHz, 915 MHz for North America and 868 MHz for Europe. In this way the standard is able to operate around the globe, although the exact specifications for each of the bands are slightly different. At 2.4 GHz there are a total of sixteen different channels available, and the maximum data rate is 250 kbps. For 915 MHz there are ten channels and the standard supports a maximum data rate of 40 kbps, while at 868 MHz there is only one channel and this can support data transfer at up to 20 kbps.

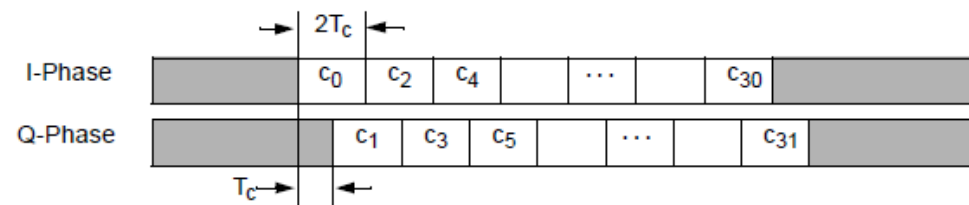
The modulation techniques also vary according to the band in use. Direct sequence spread spectrum (DSSS) is used in all cases. However for the 868 and 915 MHz bands the actual form of modulation is binary phase shift keying. For the 2.4 GHz band, offset quadrature phase shift keying (O-QPSK) is employed.

In view of the fact that systems may operate in heavily congested environments, and in areas where levels of extraneous interference is high, the 802.15.4 specification has incorporated a variety of features to ensure exceedingly reliable operation. These include a quality assessment, receiver energy detection and clear channel assessment. CSMA (Carrier Sense Multiple Access) techniques are used to determine when to transmit, and in this way unnecessary clashes are avoided.

As shown below, IEEE 802.15.4, on which ZigBee protocols are built, mandates O-QPSK modulation on various frequency carriers in 2.4 GHz range.

**6.5.2.4 O-QPSK modulation**

The chip sequences representing each data symbol are modulated onto the carrier using O-QPSK with half-sine pulse shaping. Even-indexed chips are modulated onto the in-phase (I) carrier and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. Because each data symbol is represented by a 32-chip sequence, the chip rate (nominally 2.0 Mchip/s) is 32 times the symbol rate. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by  $T_c$  with respect to the I-phase chips (see Figure 19), where  $T_c$  is the inverse of the chip rate.



**Figure 19—O-QPSK chip offsets**

**6.5.2.5 Pulse shape**

The half-sine pulse shape used to represent each baseband chip is described by Equation (1):

$$p(t) = \begin{cases} \sin\left(\pi \frac{t}{2T_c}\right), & 0 \leq t \leq 2T_c \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Figure 20 shows a sample baseband chip sequence with half-sine pulse shaping.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.1.2 Channel assignments and numbering**

A total of 27 channels, numbered 0 to 26, are available across the three frequency bands. Sixteen channels are available in the 2450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 868.3 \text{ in megahertz, for } k = 0$$

$$F_c = 906 + 2(k - 1) \text{ in megahertz, for } k = 1, 2, \dots, 10$$

and  $F_c = 2405 + 5(k - 11) \text{ in megahertz, for } k = 11, 12, \dots, 26$

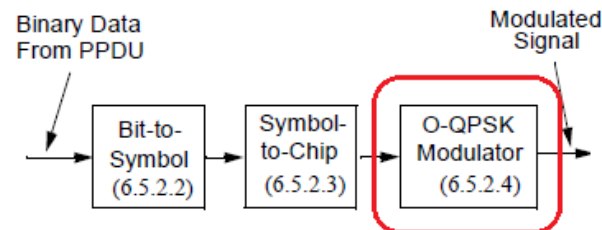
where

$k$  is the channel number.

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

IEEE  
Std 802.15.4-2003

IEEE STANDARD FOR LOCAL AND METROPOLITAN AREA NETWORKS:



**Figure 18—Modulation and spreading functions**

[https://standards.ieee.org/standard/802\\_15\\_4-2003.html](https://standards.ieee.org/standard/802_15_4-2003.html)

**6.5.2.4 O-QPSK modulation**

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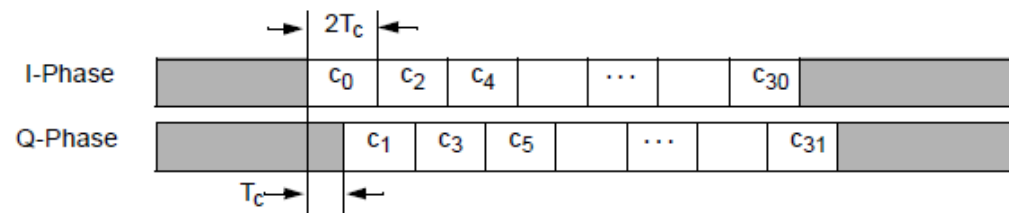


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